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Convex Optimization for Energy Management of Parallel Hybrid Electric Vehicles

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Abstract: This paper presents a comparison between two optimization methods for the energy management of a parallel hybrid electric powertrain: convex programming and Pontryagin's Minimum Principle (PMP). The objective of this comparison is to validate the analytical solution by comparing the results with the ones obtained on the original model with Dynamic Programming (DP). Therefore, before its application, some necessary approximations and convexification were made on the original nonlinear and non-convex model. The validation of the simplified model was also carried out. In this paper, two cases are studied. In the first case, the supervisory control considers only the torque split between the Internal Combustion Engine (ICE) and the Electric Machine. In the second case, a binary decision ICE On/Off is included in the optimization problem. In order to solve the problem of the binary decision, which makes the problem non-convex, a analytical solution based on PMP is then proposed. The results show that the analytical solution is close to the optimal solution given by DP.

Keywords: Energy Management Strategy, Hybrid Electric Vehicles (HEV), Convex optimization, Pontryagin's Maximum Principle (PMP), Engine On/Off.

1. INTRODUCTION

The transport sector accounts for 26% of global energy consumption (Badin, 2013). This is the reason why, in recent years, extensive research has been undertaken in order to reduce energy consumption and pollution caused by transportation. In this paper, we focus on one of the solutions for achieving a near-term reduction of energy consumption proposed by the automotive industry, which is the use of Hybrid Electric Vehicles (HEVs). HEVs consist of at least two power sources, an internal combustion engine and one or more electric motors, as well as an energy buffer, typically a battery.

This means that an energy management solution must be found between power sources in the vehicle that minimizes fuel consumption. In simulation, optimal off-line approaches are interesting for design and component sizing purposes and real-time control strategy design. There are many approaches to design an optimal energy management strategy: deterministic Dynamic Programming (DP) (Pérez et al., 2006; Debert et al., 2010), stochastic DP (Johannesson et al., 2007), and Pontryagin's Maximum Principle (Serrao et al., 2009; Kim et al., 2011). While being a globally optimal energy management, dynamic programming is computationally expensive, which limits its application to low-order systems (typically two states). As far as PMP method is concerned, its inconvenient is the sensitivity of the solution towards the boundary conditions (Serrao et al., 2011).

Recently, convex optimization (Boyd and Vendenberghe, 2004; Grant and Boyd, 2013) has attracted attention in the research field of energy management for HEVs. It is seen as an alternative method for the optimization of the power flows in HEVs due to its advantages, the most important of which is that it is computationally more efficient than DP or PMP. In Murgovski et al. (2013, 2012), convex optimization was employed to dimension the HEV powertrain especially the battery, whereas Hu et al. (2013) used it for energy efficiency analysis. In this study, we are interested in minimizing fuel consumption via convex optimization, with the use of a engine On/Off functionality to stop and start the engine during the driving cycle. This functionality enables a further fuel consumption reduction. Unfortunately, a binary variable for controlling the engine On/Off state cannot be included in a convex formulation as the set of integer numbers is not convex. To solve this kind of optimization problems, also known as a mixed integer problem, Murgovski et al. (2012) proposed that integer and binary variables should be decided a priori by heuristics. In Elbert et al. (2014), the optimal engine On/Off strategy is computed analytically using the PMP approach for a serial hybrid electric bus. In Nüesch et al. (2014), the engine On/Off and gearshift strategies are given by a combination of DP and PMP.

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This paper is organized as follows. In section 2, the vehicle model is presented. In section 3, convex modeling and optimization are proposed for a first study case where the engine is running during the driving cycle which is presented so that the optimization problem considers only the torque split of a parallel electric hybrid powertrain. In section 4, a second case is studied where the engine On/Off decision is added to the optimization problem. Here, the PMP approach on the convex model is applied to find analytically the global optimal engine state and the optimal torque split. Then, the optimal torque split is also determined by a convex solver. In section 5, simulation results obtained in the two study cases are compared to the results obtained by DP. The purpose of this comparison is to establish the performances of the simplified model and the analytical solution for real-time energy management strategies.

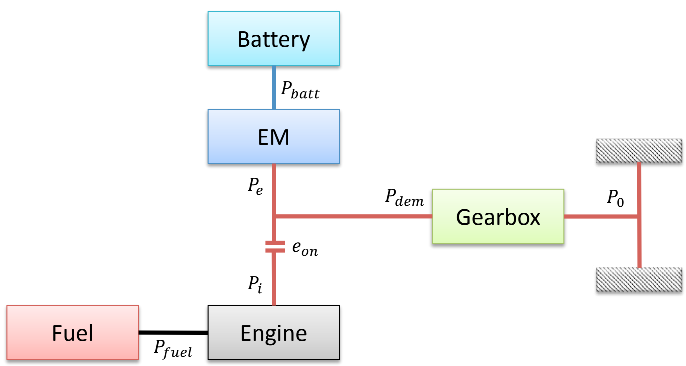

Fig. 1. Parallel HEV powertrain model with engine On/Off clutch

2. VEHICLE MODEL

In this section, the HEV model, often presented as quasi-static, is given. Fig. 1 illustrates the configuration of the powertrain architecture considered , which consists of a battery, an electric motor, an internal combustion engine delivering power to the wheels via a transmission block and a clutch e_{on}, which couples or decouples the engine with the rest of the powertrain. The vehicle dynamics is governed by the following equations:

$$F_{wheel}(t) = m_{vec}\dot{v}(t) + F_{res}(t)[N] \quad (1)$$

$$T_0(t) = F_{wheel}(t).R_{wheel}[Nm] \quad (2)$$

$$\omega_0(t) = v(t)/R_{wheel}[rad/s] \quad (3)$$

where F_{wheel} is the force at the wheels, $F_{res}(t) = F_{tires} + F_{aero}(t)$ the resistive force which includes the aerodynamic force ($F_{aero}(t) = 0.5.\rho.Scx.v^2(t)$) and the tire resistance (F_{tires})(here assumed constant), $m_{vec}[kg]$ the total vehicle mass and $R_{wheel}[m]$ the wheel radius.

2.1 Transmission

Transmission between the wheels and the crankshaft is given by the following static model:

$$\omega_{dem}(t) = \omega_0(t) r_{Gear} \quad (4)$$

$$T_{dem}(t) = \begin{cases} T_0(t)/(\eta_{Gear} r_{Gear}) \text{ if } T_0(t) \geq 0 \\ (T_0(t)\eta_{Gear})/r_{Gear} \text{ if } T_0(t) \leq 0 \end{cases} \quad (5)$$

$$P_{dem}(t) = T_{dem}(t)\omega_{dem}(t) = T_e(t)\omega_e(t) + e_{on}(t)T_i(t)\omega_i(t) \quad (6)$$

where T_0, ω_0, T_{dem}, ω_{dem}, T_e, ω_e, T_i, ω_i are torque and speed of respectively the wheel, the crankshaft, the electric motor and the internal combustion engine. e_{on} stands for the binary engine On/Off control, $e_{on}(t) = \{0, 1\}$ where $e_{on} = 1$ means that the engine is activated.

2.2 Battery

The battery is modeled as a simple resistive circuit (Badin, 2013; Murgovski et al., 2012) and the battery power is given by:

$$P_{batt}(t) = OCV(SoE)i_{batt}(t) - R_{batt}(SoE)i^2_{batt}(t)[w] \quad (7)$$

$$P_{batt}(t) = P_e(t) + P_{aux} \quad (8)$$

The State of Energy (SoE) of the battery is defined as:

$$S\dot{o}E(t) = -\frac{OCV(SoE)i_{batt}(t)}{E_{max}} \quad (9)$$

where $E_{max}[J]$ is the maximal battery energy. The current $i_{batt}[A]$ and SoE are limited by:

$$i_{batt_{min}} \leq i_{batt}(t) \leq i_{batt_{max}} \quad (10)$$

$$SoE_{min} \leq SoE(t) \leq SoE_{max}. \quad (11)$$

2.3 Engine

The engine model consists of the fuel power consumed by the engine to deliver mechanical power:

$$P_{fuel}(t) = e_{on}(t)H_f \dot{m}_f(T_i(t), \omega_i(t)) \quad (12)$$

where $\dot{m}_f(T_i(t), \omega_i(t))[g/s]$ is the fuel consumption map of the engine and $H_f[J/g]$ the fuel lower heating value.

The engine torque T_i is limited by a function of the engine speed ω_i:

$$T_{i_{min}}(\omega_i(t)) \leq T_i(t) \leq T_{i_{max}}(\omega_i(t)) \quad (13)$$

If the gear ratio is given, the engine speed is directly obtained from ω_{dem} and it is not decided by the optimization.

$$\omega_i(t) = \omega_{dem}(t) \quad (14)$$

2.4 Electric Motor (EM)

The electric motor model expresses the electric power produced by EM which includes the mechanical power delivered and the losses obtained from the specific power loss of the EM $loss(T_e(t), \omega_e(t))$. So, the electric power (P_e) produced by the EM has the following expression:

$$P_e(t) = T_e(t)\omega_e(t) + loss(T_e(t), \omega_e(t)) \quad (15)$$

Here also, the EM speed is obtained from ω_{dem}.

$$\omega_e(t) = \omega_{dem}(t) \quad (16)$$

The EM torque is limited by torque limits depending on the EM speed:

$$T_{e_{min}}(\omega_e(t)) \leq T_e(t) \leq T_{e_{max}}(\omega_e(t)) \quad (17)$$

3. CONVEX OPTIMIZATION WITHOUT ENGINE ON/OFF STRATEGY

As can be seen from Elbert et al. (2014); Nüesch et al. (2014); Yuan et al. (2013), there are many approaches to